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Voltage Harmonics Measuring Issues in Medium Voltage Systems

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1. Introduction

Voltage harmonic distortion level is one of the significant parameters of power quality in power system. Numerous problems related to voltage and current harmonic effects for contemporary power systems are commonly observed nowadays. Levels and spectral content of voltage distortions injected into electric power grids are tending to increase despite the fact that the acceptable levels are determined by numerous regulations. Voltage distortion assessments, especially in middle and high voltage grids, are usually based on measurements in which voltage transformers are commonly used. The transfer ratio of a voltage transformer fed by distorted primary voltage with harmonic components of frequency higher than fundamental can be different for high frequency components in comparison with the fundamental frequency.

During the last decades primary problems related to voltage distortions have been usually encountered in frequency range up to 40th harmonic, mostly in LV grids. Nowadays, due to the evident increase of the overall power of nonlinear power electronic loads connected to grid and higher modulation frequencies widely used, distorted voltage propagates deeply into MV grids and goes evidently beyond frequency of 2 kHz.

This chapter presents problems of voltage harmonic transfer accuracy through voltage transformers which are usually used for power quality monitoring in medium and high voltage grids (Kadar at al., 1997, Seljeseth at al., 1998, Shibuya at al., 2002, Mahesh at al., 2004, Yao Xiao at al., 2004, Klatt at al., 2010). A simplified lumped parameters circuit model of the voltage transformer is proposed and verified by simulation and experimental investigations. A number voltage transformers typically used in medium voltage grid have been tested in the conducted disturbances frequency range up to 30 MHz. The obtained results prove that broadband voltage transfer function of the voltage transformer usually exhibits various irregularities, especially in high frequency range, which are primarily associated with windings' parasitic capacitances.

Frequency dependant voltage transfer characteristic of voltage transformer induces extra measurement errors which have to be taken into account in order to achieve desired final relatively high accuracy required for power quality monitoring systems.

2. Circuit modelling of voltage transformers

Classical voltage transformer (VT) is a two or three winding transformer with a relatively high transformation ratio and low rated power, intended to supply only measuring inputs

of metering apparatus or protection relays extensively used in power system. VT are mostly used in medium voltage (MV) and high voltage (HV) systems for separation of the measuring and protecting circuit from high voltage hazard.

Rated primary voltages of VTs, typically used in power system, have to correspond to rated voltages of MV and HV transmission lines in particular power system. Secondary rated voltage levels usually used in a typical measuring and protection systems are: 100 V , $100/3\text{ V}$, $100/\sqrt{3}\text{ V}$ what results with transformation ratios of the order from few tenth up to few hundredths for MV VT and more than thousand for HV VT. Such a high transformation ratio and low rated power of VT influence significantly its specific parameters, especially related to performance in wide frequency range.

The classical equivalent circuit model of two windings transformer widely used for modelling VT for power frequency range is presented in Fig.1. This model consists of leakage inductances of primary winding L_p and secondary winding L_s and magnetizing inductance L_m . Corresponding resistances represent VT losses in magnetic core R_m and windings R_p , R_s .

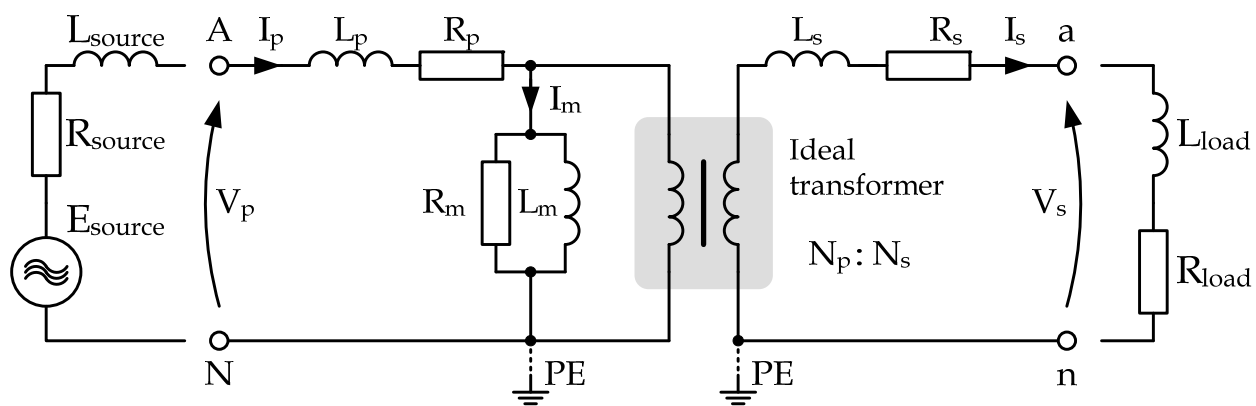


Fig. 1. Classical equivalent circuit model of a voltage transformer

For VT operated under power frequency and rated load presented circuit model can be simplified radically because magnetizing inductance L_m is usually many times higher than leakage inductances $L_m \gg L_p, L_s$ and VT nominal load impedance $Z_{load} = R_{ld} + j\omega L_{load}$ is usually much higher than secondary leakage impedance $Z_s = R_s + j\omega L_s$ ($Z_{ld} \gg Z_s$). This assumption cannot be adopted for frequencies varying far from power frequency range because VT reactance change noticeably with frequency what results with VT transformation ratio change.

Based on this model, which characterizes two not ideally coupled inductances, frequency dependant transfer characteristic for frequencies higher than the nominal (50 or 60 Hz) can be estimated as well. Theoretical wideband transfer characteristic of VT modelled by using classic circuit model is presented in Fig.2 where low corner frequency of pass band f_{low} and high corner frequency of pass band f_{high} can be defined based on 3 dB transfer ratio decrease margin assumption.

Low and high frequency response of VT can be determined analytically based on VT classic circuit model parameters. For wideband analysis simplification classical circuit model of VT can be represented as a serial connection of high pass filter (HPF), ideal transformer and low pass filter (LPF) (Fig.3). According to this simplification, the pass band characteristic of high

pass LC filter is mainly correlated to VT primary side parameters (R_{HPF} , L_{HPF}) and the pass band characteristic of low pass LC filter is mainly correlated to parameters of secondary side (R_{LPS} , L_{LPF}).

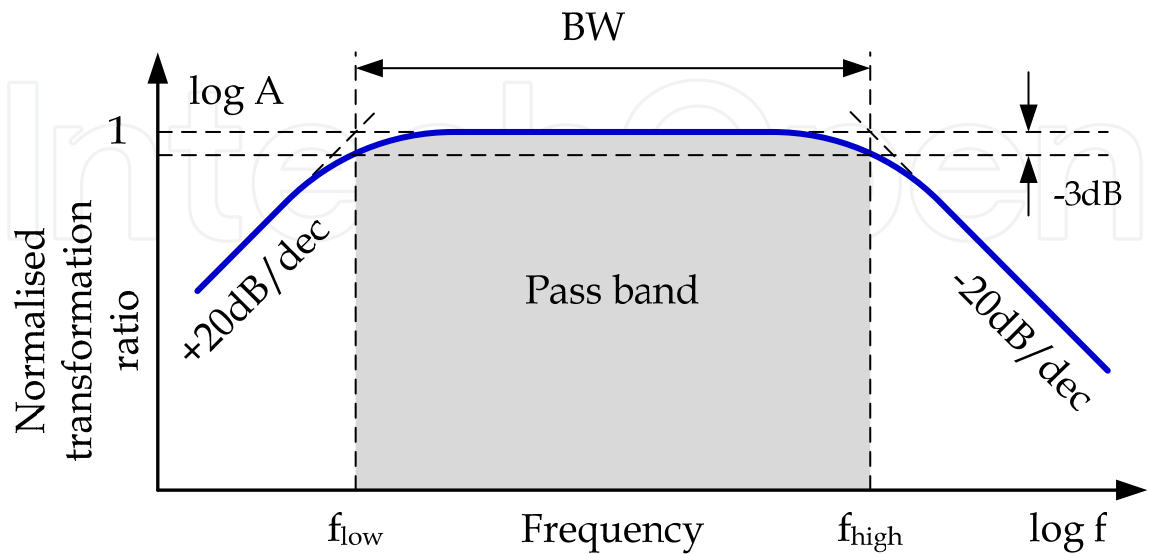


Fig. 2. Theoretical transfer ratio wideband characteristic of VT modelled by classical circuit model

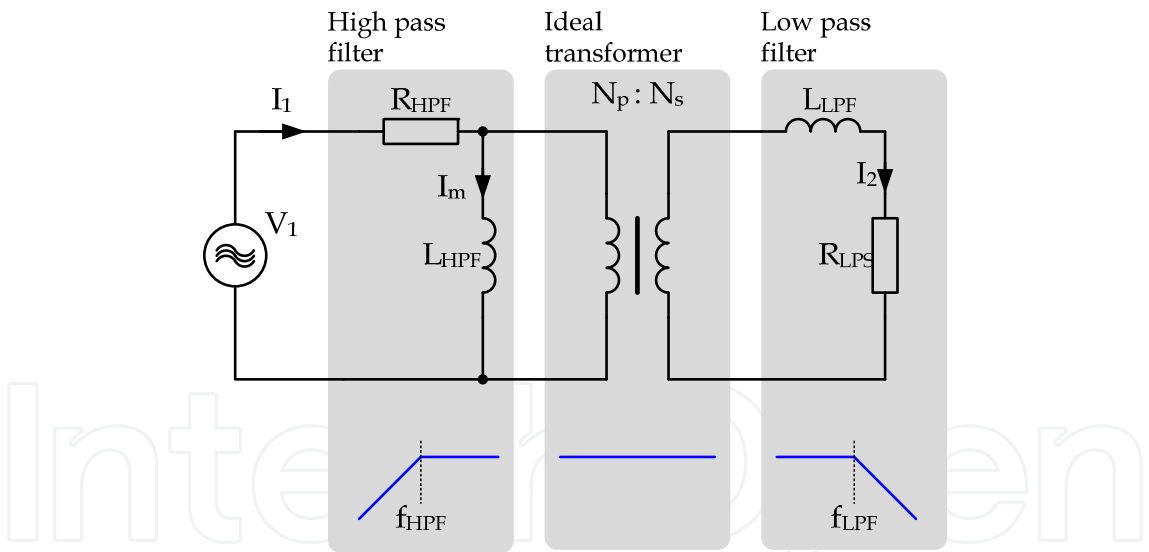


Fig. 3. High pass and low pas filter representation of VT circuit model

Based on this assumption the low corner frequency f_{low} of VT transfer characteristic can be easily defined by formula (1) and high corner frequency f_{high} by formula (2).

$$f_{low} = f_{HPF} = \frac{R_{HPF}}{2\pi L_{HPF}} \tag{1}$$

$$f_{high} = f_{LPF} = \frac{R_{LPS}}{2\pi L_{LPF}} \tag{2}$$

Wideband analysis of VT transfer characteristic requires taking into account also external impedances of measured voltage source and VT load. Therefore, equivalent resistance of high pass filter R_{HPF} can be defined as a sum of VT primary winding resistance and primary voltage source resistance R_{source} (3). Respectively high pass filter equivalent inductance L_{HPF} is a sum of VT magnetizing inductance L_m , primary winding leakage inductance L_p and primary voltage source inductance L_{source} (4).

$$R_{HPF} = R_p + R_{source} \quad (3)$$

$$L_{HPF} = L_p + L_m + L_{source} \quad (4)$$

Analogous equivalent parameters for LPF are as follows:

$$R_{LPF} = R_p + \eta^2 R_s + \eta^2 R_{load} \quad (5)$$

$$L_{LPF} = L_p + \eta^2 L_s + \eta^2 L_{load} \quad (6)$$

For RL type low and high pass filters 3 dB pass band margin is obtained for the frequency at which magnitudes of filter resistance R is equal to magnitude of filter reactance $X_L = 2\pi fL$. According to this formula, the corner frequency of low pass equivalent filter f_{LPF} determines the lowest signal frequency f_{low} transformed by VT (7) and the corner frequency of high pass equivalent filter f_{HPF} determines the highest signal frequency f_{high} transformed by VT (8), where $\eta = N_p/N_s$ is a VT winding ratio.

$$f_{low} = \frac{R_p + R_{source}}{2\pi(L_p + L_m + L_{source})} \quad (7)$$

$$f_{high} = \frac{R_p + \eta^2 R_s + \eta^2 R_{load}}{2\pi(L_p + \eta^2 L_s + \eta^2 L_{load})} \quad (8)$$

Assuming that magnetizing inductance L_m of a typical VT is much higher than leakage inductance L_p of primary winding ($L_m \gg L_p$) and also much higher than primary voltage source inductance ($L_m \gg L_{source}$) the equation (7) can be simplified to (9). Similarly, because resistance of secondary winding R_s is usually much lower than load resistance R_{load} ($R_s \ll R_{load}$) the equation (8) can be simplified to (10).

$$f_{low} \approx \frac{R_p + R_{source}}{2\pi \cdot L_m} \quad (9)$$

$$f_{high} \approx \frac{\eta^2 R_{load}}{2\pi(L_p + \eta^2 L_s + \eta^2 L_{load})} \quad (10)$$

Finally, VT bandwidth BW can be estimated by using formula (11) and relative bandwidth $BW [\%]$ using formula (12).

$$BW = f_{high} - f_{low} = \frac{\eta^2 R_{Load}}{L_p + \eta^2 L_s + \eta^2 L_{Load}} - \frac{R_p + R_{source}}{L_m} \quad (11)$$

$$BW[\%] = 2 \cdot \frac{f_{high} - f_{low}}{f_{high} + f_{low}} = 2 \cdot \frac{\eta^2 L_m R_{load} - (L_p + \eta^2 L_s + \eta^2 L_{Load})(R_p + R_{source})}{\eta^2 L_m R_{load} + (L_p + \eta^2 L_s + \eta^2 L_{Load})(R_p + R_{source})} \quad (12)$$

Summarizing, based on classical circuit model analysis, low frequency response of VT is mostly dependant on its leakage to magnetizing impedance ratio which limits transfer characteristic in low frequency range. In applications where voltage source impedance is relatively high and cannot be neglected an extra pass band limitation is observed due to its influence (Fig.4). High frequency response of VT is dependant mainly on its leakage impedance to load impedance ratio which limits transfer characteristic in high frequency range. Increase of load impedance extends bandwidth of VT towards higher frequencies. Theoretically, for very low VT load its pass band can be very wide from the magnetic coupling point of view, nevertheless parasitic capacitances usually limit noticeably VT pass band in high frequency range.

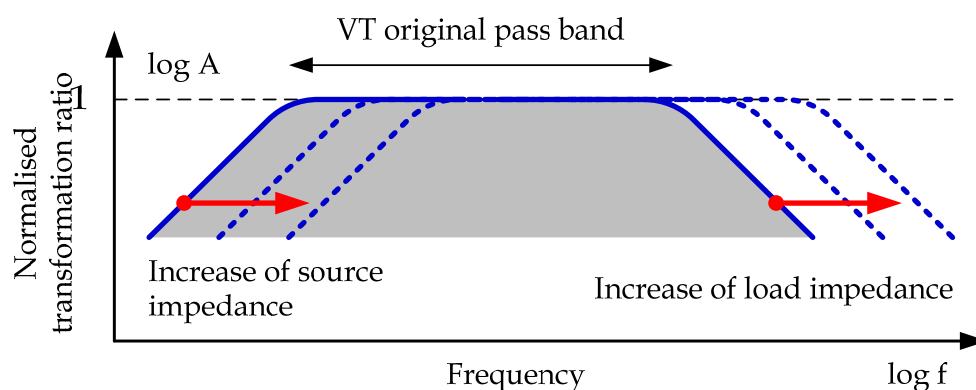


Fig. 4. Influence of source and load impedance on the VT pass band

3. Broadband modelling of voltage transformers

Modelling of VT in a wide frequency range using classical circuit model is usually not adequate enough. The foremost reasons for the inadequacy of the classical circuit model are the parasitic capacitances of windings and frequency dependant voltage source and VT load impedances. Parasitic capacitances existing in windings change noticeably the transformation ratio characteristic, particularly in high frequency range.

Parasitic capacitance is an effect of proximity of windings and its sections to each other and to other conductive usually grounded elements, like for example magnetic core, electric shields and other conductive elements of VT. Parasitic capacitances of VT windings are usually unwanted and unluckily unavoidable; there are only various techniques used to reduce its values or change distribution. Parasitic capacitances of VT change radically its behaviour in high frequency range usually reduce evidently the pass band bandwidth with flat transfer characteristic. Parasitic capacitances of VT windings have distributed nature strictly correlated with particular winding arrangement, therefore their identification and modelling is problematic (Vermeulen at al., 1995, Islam at al., 1997, Luszcz, 2004a, 2004b,

Mohamed et al., 2008). Consequences of parasitic capacitances are especially significant for multilayer windings with high number of turns which is characteristic for high voltage and low power transformers like VT. The most essential categories of partial parasitic capacitances occurring in typical VT windings are presented in Fig. 5.

Identification of not equally distributed partial parasitic capacitances for particular VT require detailed specification of winding arrangement, is extremely elaborative and usually do not provide adequate enough results. Difficulties of parasitic capacitances identification can be reduced by defining lumped equivalent capacitances which represent groups of many partial capacitances related to entire winding or part of windings; for example single layer of winding. Noticeable simplification of parasitic capacitances distribution in VT winding can also be achieved by changing winding arrangement and introducing windings' shields. Example of influence of windings' shields on parasitic capacitances distribution is presented in Fig. 6 where the inter-winding capacitance, usually most noticeable, is radically reduced by introducing additional winding-to-shield capacitances.

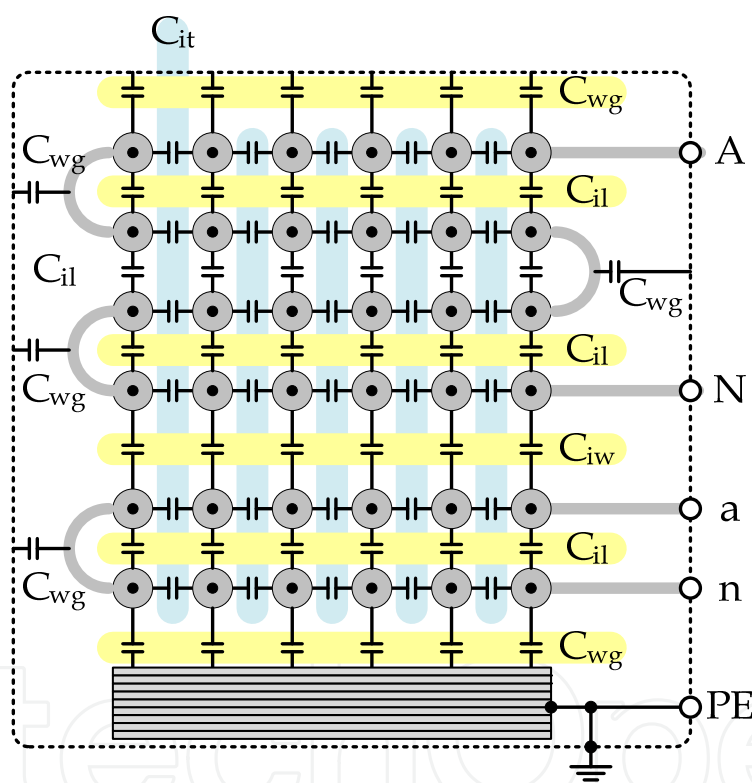


Fig. 5. Major categories of parasitic capacitances occurring in VT windings: C_{wg} – winding to ground, C_{il} – interlayer, C_{it} – inter-turn, C_{iw} – inter-winding

Use of lumped representation of parasitic capacitances allows reducing winding model complexity and consequently simplifies noticeably its parameters identification process. A possible to apply winding model simplification level should be closely correlated with the expected adequacy in a given frequency range and depends evidently on particular winding arrangement complexity. Commonly, three methods of winding parasitic capacitances circuit representations are used to model transformer windings (Fig. 7):

- winding terminals related – where all defined lumped equivalent capacitances are connected to windings' terminals only,

- partially distributed - lumped parasitic capacitances are specified for most representative internal parts of winding, like for example windings layers, winding shields,
- fully distributed - windings are modelled as a series and parallel combination of inductances and capacitances which form ladder circuit with irregular parameter distribution.

Generally more detailed parasitic capacitances representation allows obtaining higher level of model adequacy in wider frequency range. Nevertheless because of identification problems the model complexity should be kept within a reasonable level to allow achieving high usefulness.

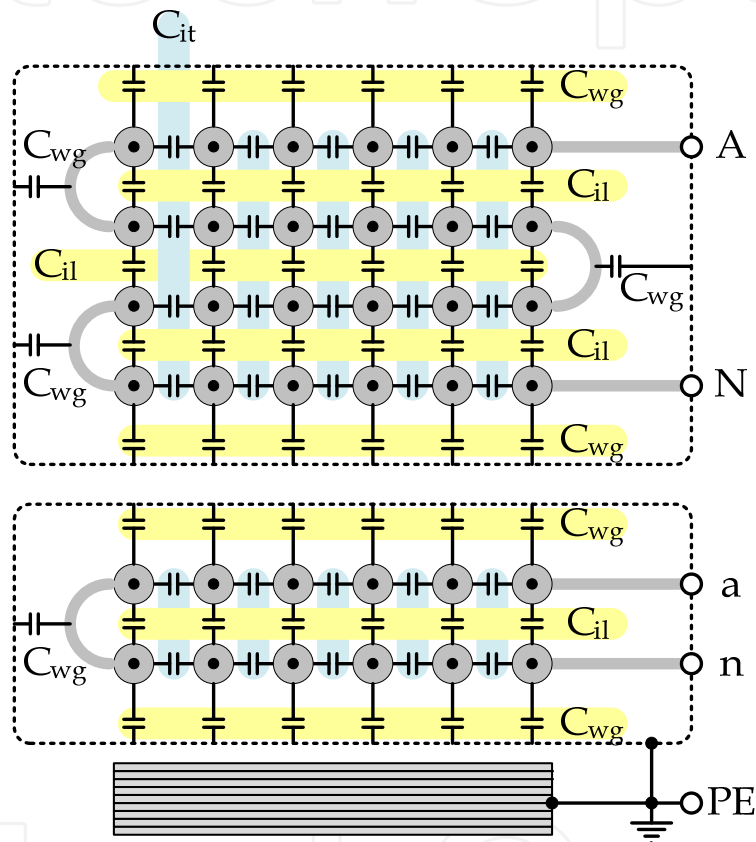


Fig. 6. Parasitic capacitances arrangement in shielded VT windings

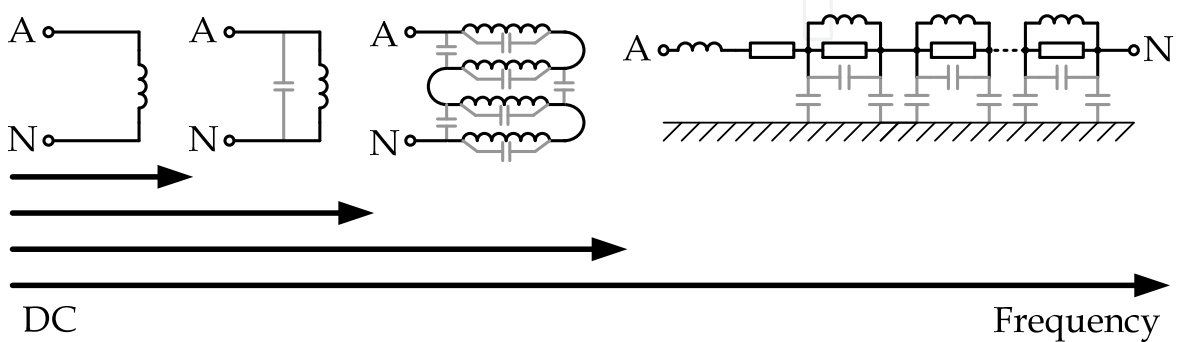


Fig. 7. Typical circuit representations of winding parasitic capacitances

The influence of winding parasitic capacitances on the VT transfer ratio also depends on winding grounding method used in measuring application. In Fig. 8 two mostly used VT winding configurations are presented, where primary winding is connected to measured voltage in a different way. VTs configured as one-side grounded primary and secondary windings are commonly used for phase voltage measurement in power system, while VT floating primary winding allows for direct measurement of inter-phase voltages (Fig.9). The analysis of VT transfer characteristic for VT with both windings grounded is noticeably simpler, therefore presented further analysis based on the proposed circuit model and experimental tests have been limited to this case.

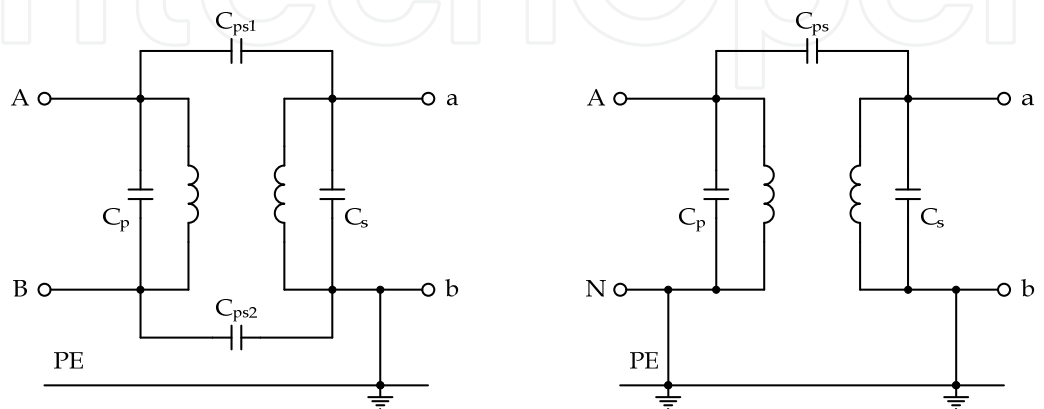


Fig. 8. Different configurations of VT primary winding grounding

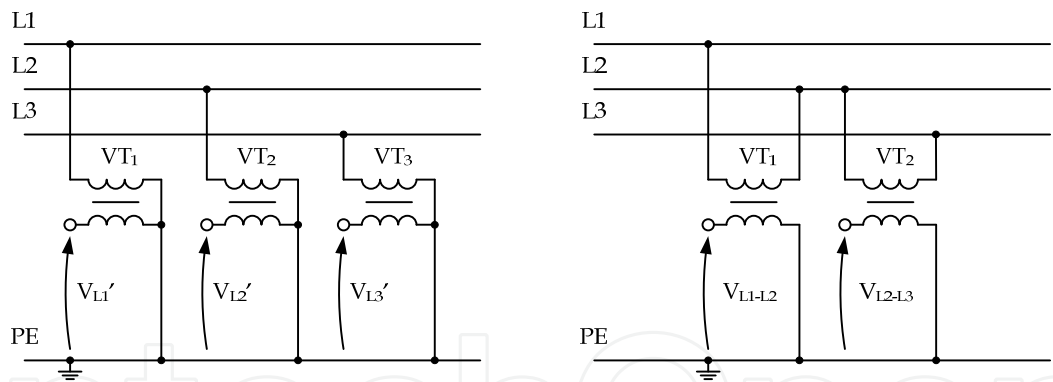


Fig. 9. Typical VT connection for phase and inter-phase voltage measurement in tree phase power system

4. Wideband parameters identification of voltage transformer

Particular voltage transformation ratio of VT in high frequency range is closely related to impedance-frequency characteristics of primary and secondary windings. Therefore measurement results of VT magnetizing and leakage impedances within the investigated frequency range are the fundamental data resources for analysis its broadband behaviour. Measurement of VT impedances can be done similarly as in a typical no load and short circuit tests recommended for power frequency with the use of sweep frequency excitation. Examples of magnitude and phase characteristics of the magnetizing impedance of investigated VT are presented in Fig. 10 and leakage impedance in Fig. 11.

Concise analysis of the exemplary magnetizing and leakage impedance characteristics allow estimating characteristic frequency ranges correlated with the VT different performance. Firstly, measured impedances exhibit characteristic serial resonances which appear in frequency range around $f_{r1} \approx 150 \text{ Hz}$ and around $f_{r2} \approx 200 \text{ kHz}$ for magnetizing and leakage impedances respectively. On the magnetizing impedance characteristic, between these two frequencies f_{r1} and f_{r2} , serial resonance is clearly visible for the frequency range around $f_{r3} \approx 2 \text{ kHz}$. These three particular resonance frequencies f_{r1} , f_{r2} , f_{r3} divide the frequency spectrum into three sub-ranges closely related to VT behaviour. Secondly, in the frequency range between around 3 kHz and 20 kHz several less meaningful resonances can be observed which are correlated with local resonances appearing in winding internal subsections.

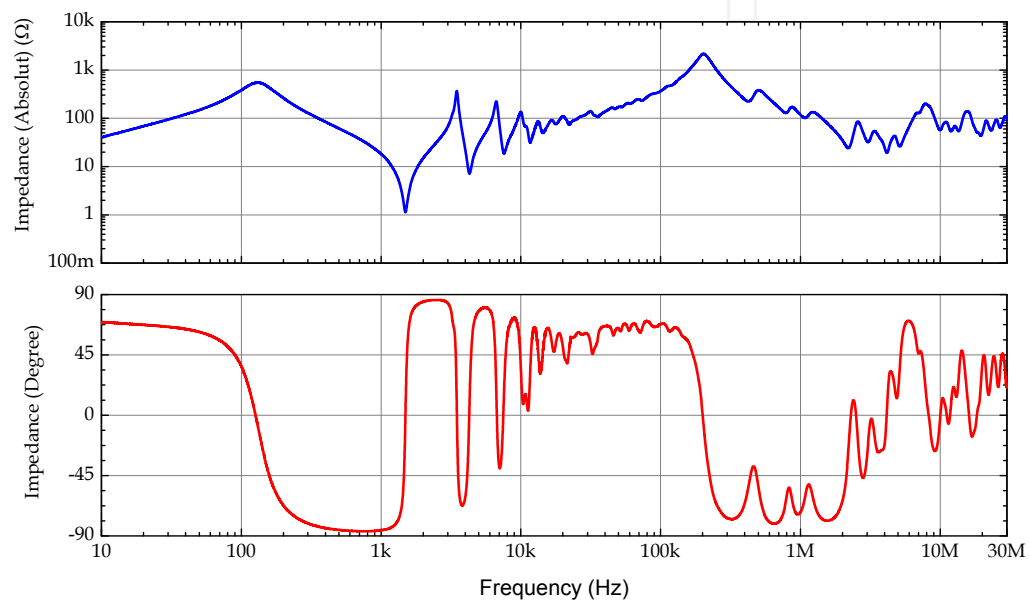


Fig. 10. Measured magnetizing impedance-frequency characteristics of investigated VT

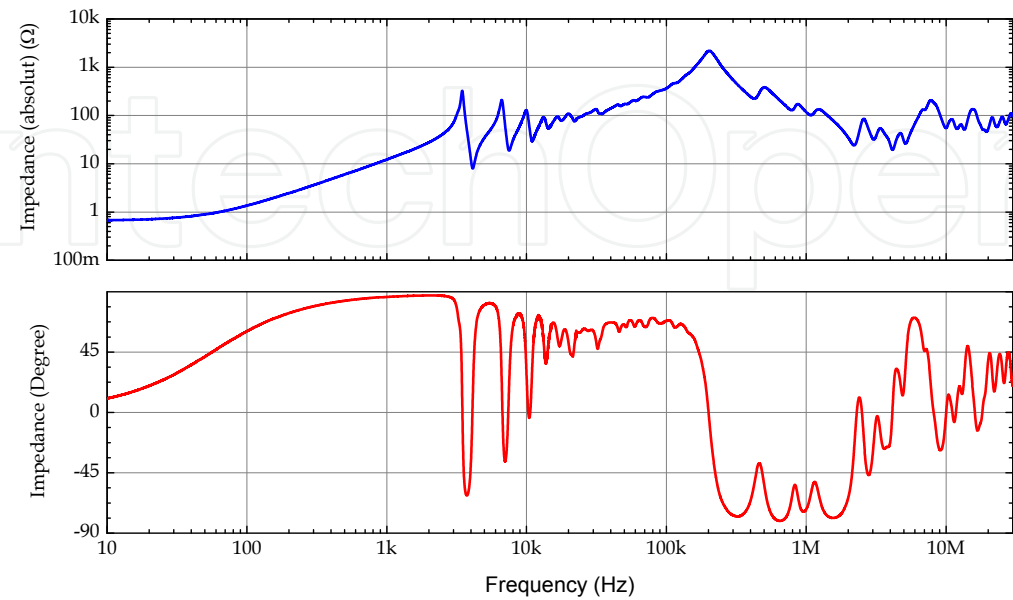


Fig. 11. Measured leakage impedance-frequency characteristics of investigated VT

Simplified representation of VT magnetizing and leakage impedances is presented in Fig. 13, where characteristic resonance frequencies f_{r1} , f_{r2} , f_{r3} and related to them frequency bands B_1 , B_2 , and B_3 are emphasized. The frequency band B_1 below f_{r3} can be characterized as a VT pass band where the magnetizing impedance is much higher than the leakage impedance; therefore in this frequency range between primary and secondary windings magnetic coupling effect is dominating. In the frequency band B_2 , between f_{r2} and f_{r3} , the magnetizing impedance values are comparable to the leakage impedance, what weakening noticeably the magnetic coupling effect and the influence of VT load impedance on the transfer ratio characteristic became significant. In the frequency range above f_{r2} (band B_3) the capacitive character of magnetizing and leakage impedances of VT is dominating, what means that capacitive type of coupling between VT windings is predominant.

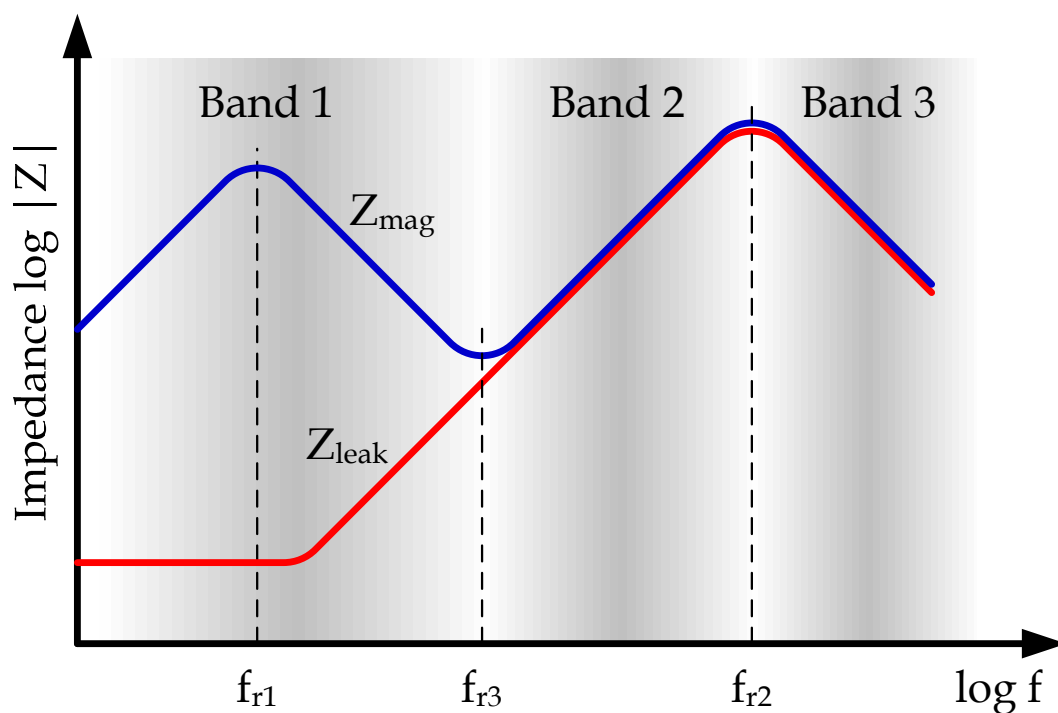


Fig. 12. Simplified representation of VT magnetizing and leakage impedance-frequency characteristics

The developed wideband circuit model of VT is based on the classical circuit model of the magnetic coupling presented in previous subsection. Distributed parasitic capacitances of VT windings are modelled by the lumped capacitances connected only to windings terminals (Fig.13). This assumption reduces noticeable model complexity and allows determining parasitic capacitances based on the measured windings impedances. In the analysed case primary and secondary windings of investigated VT are one side grounded which limits furthermore the number of lumped capacitances necessary to be determined. Detailed analysis of VT magnetizing and leakage impedance-frequency characteristics and identification of specific resonance frequencies allows estimating parameters of the VT circuit model presented in Fig.13 in the analysed frequency range. The method of determination parasitic lumped capacitances is based on identification of resonance frequencies which are usually possible to determine using the measured impedance

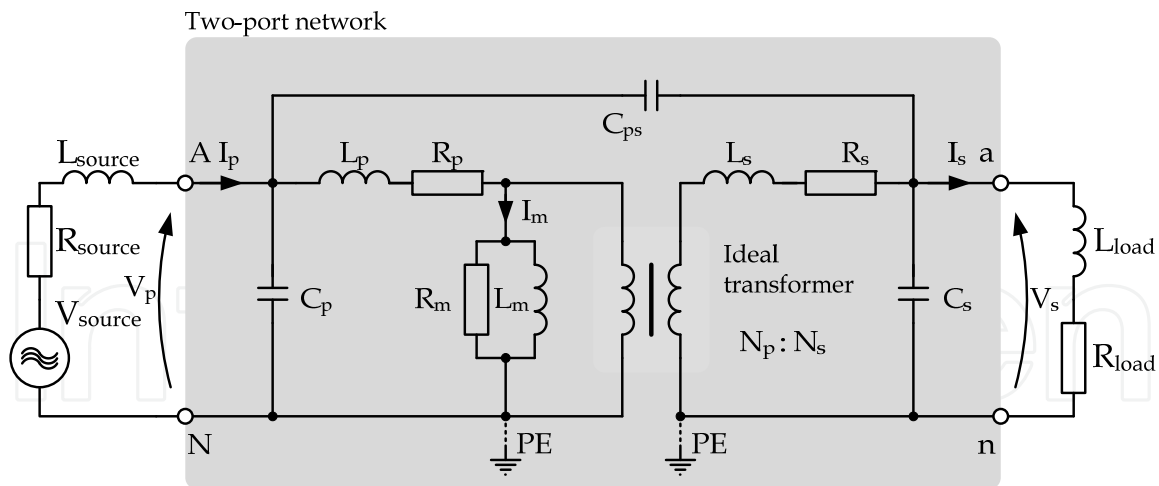


Fig. 13. Broadband circuit model of the VT with lumped parasitic capacitances referenced to windings terminals: C_p – primary winding, C_s – secondary winding, C_{ps} – inter-winding

characteristics (Fig. 10 and 11). Impedance characteristic below resonance frequencies allows to determine adequate inductances and corresponding parasitic capacitances which can be calculated based on the identified resonance frequencies (13), (14). Winding inductances and parasitic capacitances vary slightly with frequency increase therefore matching approximations should be taken into account for simplification.

$$f_{r1} \approx \frac{1}{2\pi\sqrt{L_m(C_p + C_s)}} \tag{13}$$

$$f_{r2} \approx \frac{1}{2\pi\sqrt{(L_p + L_s)L_m(C_s + C_{ps})}} \tag{14}$$

For analytical evaluation of proposed circuit model two-port network representation can be efficiently used (15) and the final formula (16) for the VT transfer function characteristic vs. frequency can be determined. Transmission matrix representation of the defined two-port network model of VT allows furthermore for consideration of the influence of source impedance (17) and load impedances (18) which have to be considered in broadband analysis.

$$\begin{bmatrix} \underline{V}_p(j\omega) \\ \underline{I}_p(j\omega) \end{bmatrix} = \begin{bmatrix} \underline{A}(j\omega) & \underline{B}(j\omega) \\ \underline{C}(j\omega) & \underline{D}(j\omega) \end{bmatrix} \begin{bmatrix} \underline{V}_s(j\omega) \\ \underline{I}_s(j\omega) \end{bmatrix} \tag{15}$$

$$\underline{H}(j\omega) = \frac{\underline{U}_s(j\omega)}{\underline{U}_{source}(j\omega)} = \frac{\underline{Z}_{load}}{\underline{A}\underline{Z}_{load} + \underline{B} + \underline{C}\underline{Z}_{source}\underline{Z}_{load} + \underline{D}\underline{Z}_{source}} \tag{16}$$

$$\underline{Z}_{source} = R_{source} + j\omega L_{source} \tag{17}$$

$$\underline{Z}_{load} = R_{load} + j\omega L_{load} \quad (18)$$

The A, B, C and D coefficients of transmission matrix T (19) can be used for fully characterizing electrical performance of the VT in any external condition and its frequency characteristics can be defined by measurement for a specific load condition. Based on the relationship resulting from (15); $A(j\omega)$ is a complex voltage transfer function at no load (20), $B(j\omega)$ is a complex transfer impedance with the secondary winding shorted (21), $C(j\omega)$ is a complex transfer admittance at no load (22), $D(j\omega)$ is a complex current transfer function with the secondary winding shorted (23).

$$T = \begin{bmatrix} \underline{A}(j\omega) & \underline{B}(j\omega) \\ \underline{C}(j\omega) & \underline{D}(j\omega) \end{bmatrix} \quad (19)$$

$$A(j\omega) = \left. \frac{V_p(j\omega)}{\underline{V}_s(j\omega)} \right|_{I_s=0} \quad (20)$$

$$B(j\omega) = \left. \frac{V_p(j\omega)}{\underline{I}_s(j\omega)} \right|_{V_s=0} \quad (21)$$

$$C(j\omega) = \left. \frac{I_p(j\omega)}{\underline{V}_s(j\omega)} \right|_{I_s=0} \quad (22)$$

$$D(j\omega) = \left. \frac{I_p(j\omega)}{\underline{I}_s(j\omega)} \right|_{V_s=0} \quad (23)$$

5. Simulation investigation of voltage transformer circuit model

The investigated circuit model of VT can be examined by simulation in any PSpice compatible environment in the conducted disturbance propagation frequency range up to 30 MHz. The essential verification of VT model adequacy has been done by determining magnetizing and leakage impedance characteristics which allows verifying model representation adequacy of magnetic coupling between windings. Obtained impedance characteristics are presented in Fig.14 and should be compared to the corresponding measurement results presented in Fig.10 and Fig.11.

Obtained simulation results confirm generally broad-spectrum impedance variations within few dB accuracy margin but many greater than few dB discrepancies can be observed especially close to the resonance frequencies and in frequency range above a few kHz. It should be underlined that the expected compliance level cannot be too high because of many simplifications implemented in the model. The most significant limitation of the evaluated circuit model is associated with lumped representation of winding parasitic capacitances with relation to windings terminals only.

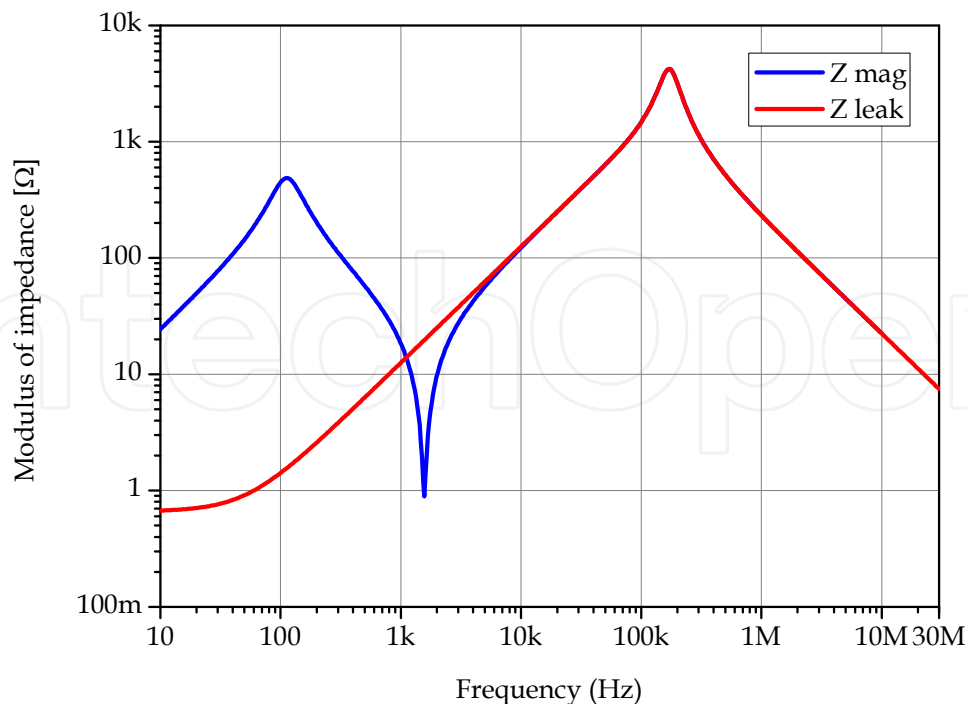


Fig. 14. Magnetizing and leakage impedances of the evaluated VT calculated using developed circuit model

Despite the relatively low accuracy, the developed VT circuit model can be used for simulation analysis of the influence of the VT parameters and its load on the voltage transfer ratio frequency characteristic. The exemplary simulation results of VT voltage transfer ratio characteristics calculated for different resistive loads are presented in Fig. 15.

Based on the presented simulation results it can be noticed that the VT voltage transfer characteristic change essentially for frequencies higher than the main resonance frequency observed on the leakage impedance, which is about 100 kHz for the evaluated case. Above this frequency VT voltage transfer ratio depends mainly on winding parasitic capacitances and magnetic coupling between windings becomes less meaningful.

Simulation results demonstrate that in frequency range close to leakage impedance resonance VT load has the major influence on the VT transfer characteristic. Increase of resistive VT load reduces significantly VT voltage transfer ratio around this frequency. Obtained simulation results confirm that according to the analytical investigation Eq. (8), VT load rate has significant influence on VT performance in high frequency range and limits usually its pass band. According to the presented simulated transfer characteristics it is possible to expand the pass band width by lowering the VT load. Unfortunately, low VT load can intensify adverse effects of any resonances which might arise in VT.

VT load character, capacitive or inductive, has also essential influence on the voltage transfer ratio frequency characteristics. Simulation results for VT loaded with the same impedance determined for power frequency and different power factor (1 resistive, 0.7 inductive and 0.7 capacitive) is presented in Fig. 16. The obtained results demonstrate positive impact of inductive character of VT load on the pass band width. Inductive VT load broadens the pass band towards the resonance frequency and causes effects of resonance to be more sharp. In the evaluated case, the change of the VT load from purely resistive to inductive ($PF=0.7$ @ 50 Hz) increases the 3 dB cut-off frequency few times.

Capacitive character of VT load induces opposite effect and narrows VT pass band width significantly. Similarly, the change of VT load from purely resistive to capacitive ($PF=-0.7$ @ 50 Hz) decrease of VT pass band width is about tens times.

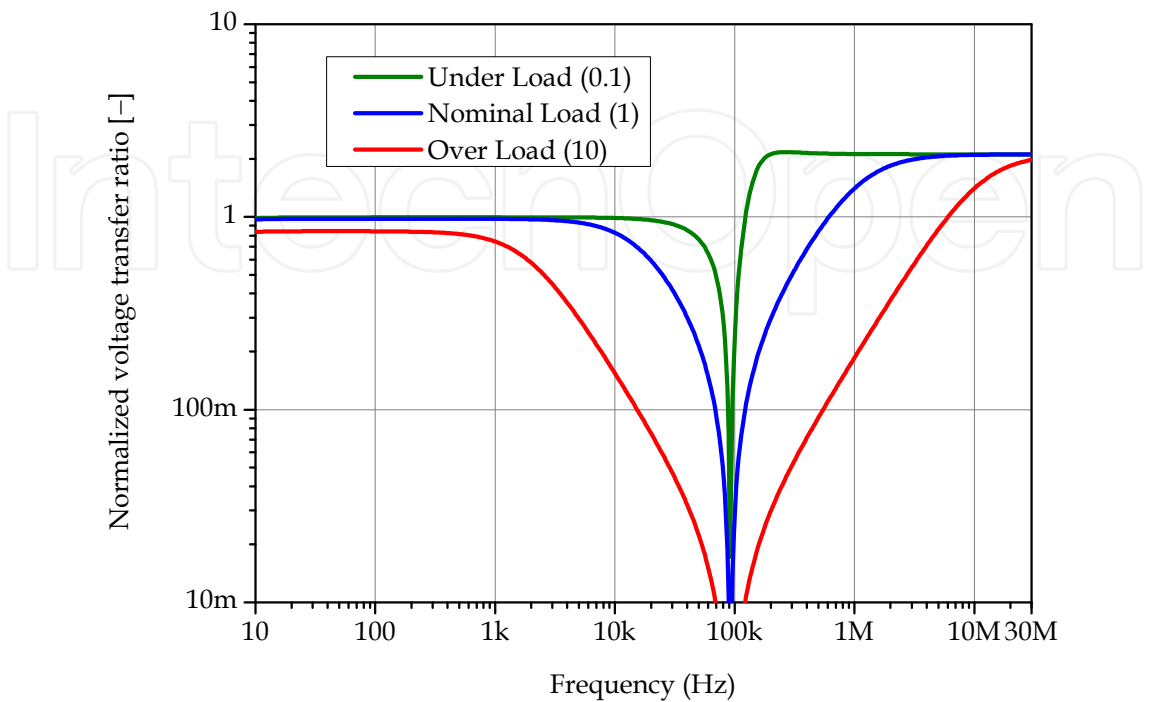


Fig. 15. Simulation results of the influence of resistive load of VT on voltage transfer ratio frequency characteristic

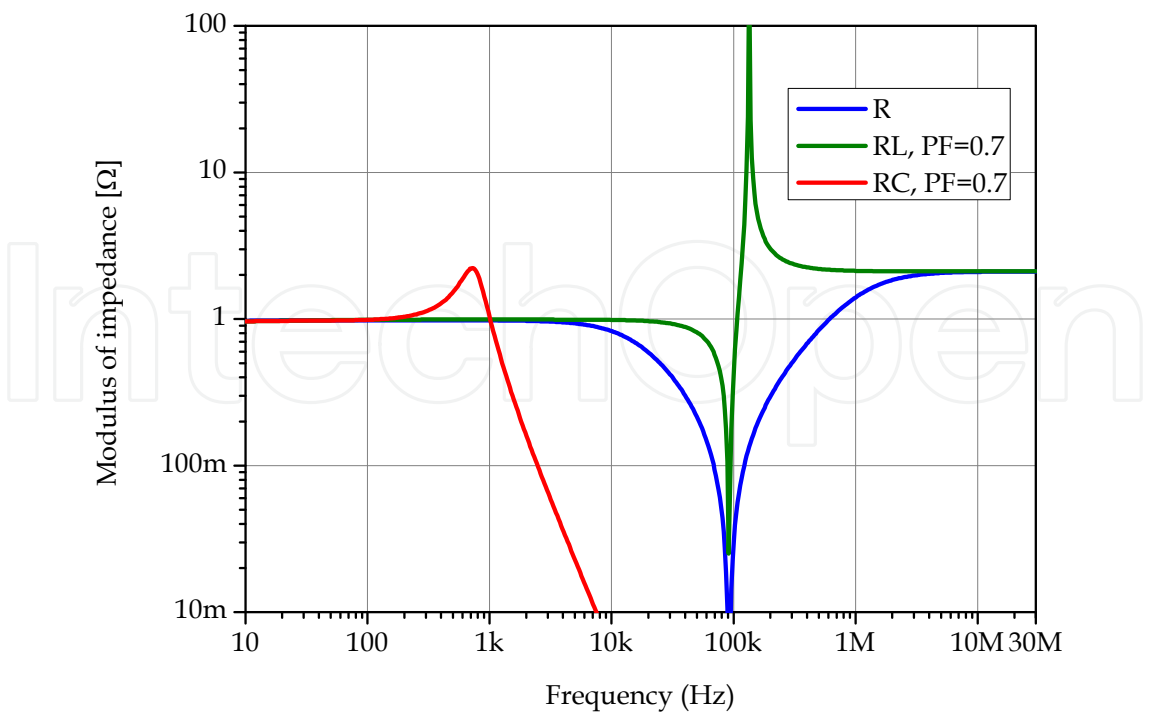


Fig. 16. Influence of the character of VT load on voltage transfer ratio frequency characteristic – simulation results

6. Experimental tests of voltage transformer transfer characteristic

Experimental investigations have been done for voltage transformers typically used in MV power system with primary and secondary windings grounded. Exemplary measurement results presented in this chapter have been obtained for VT of 50 VA rated power and 20 kV/0.1 kV nominal transformation ratio. Parameters of the proposed VT circuit model for simulation have been identified by analysis of secondary windings impedance-frequency characteristics measured for no load condition (magnetizing inductance – Fig.10) and short circuit condition (leakage inductance – Fig.11). Measurements have been done in frequency range from 10 Hz up to 30 MHz, which is a range typically used for the analysis of conducted disturbances in power system. Particular attention has been paid to the frequency range below 10 kHz which is obligatory for power quality analysis, especially for analysis of power system voltage harmonics related phenomena.

The measured voltage transfer characteristics of evaluated VT for nominal load and no load conditions are presented in Fig. 17. Based on these results the 3 dB high frequency pass band of the evaluated VT can be estimated to be about 2 kHz. For frequencies higher than 2 kHz a number of less meaningful resonances are clearly visible on the VT voltage transfer characteristic which are not adequately characterized by the evaluated circuit model. This inadequacy is associated with extra internal resonances appearing in windings which cannot be properly represented by lumped parasitic capacitances referenced only to windings terminals. In order to model these phenomena more complex circuit model are required which take into account more detailed distributed representation of partial parasitic capacitance of VT primary winding.

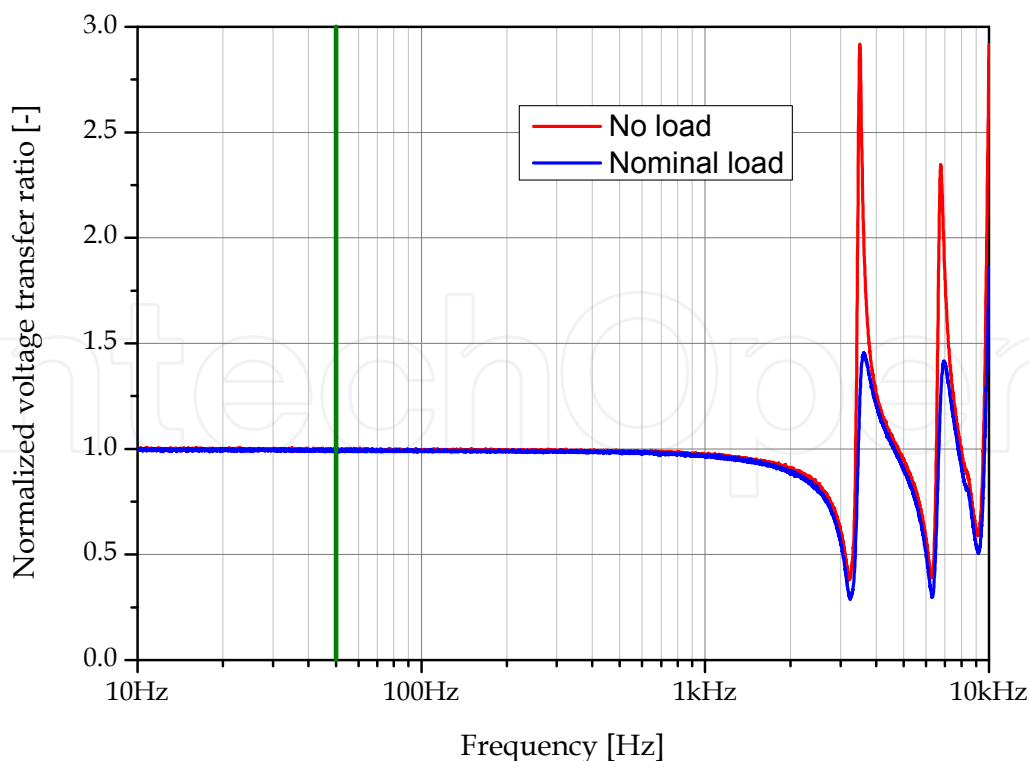


Fig. 17. Normalized voltage transfer ratio of the VT for no load and nominal resistive load

Comparison of voltage transfer characteristic measured for no load and nominal resistive load condition confirms that the influence of the level of the resistive load is mostly observable for frequencies close to the resonance frequencies. For these frequency ranges the voltage transfer ratio can vary even few times due to the VT load change.

Comparison of VT leakage and magnetizing impedances allow for preliminary approximation of the VT pass band cut-off frequency. In Fig. 18 correlation between VT impedances and the measured voltage transfer ratio is presented. Based on this comparison it can be noticed that:

- firstly, for the frequency range where magnetizing inductance is evidently higher than leakage impedance (Band 1 according to Fig. 12) the magnetic coupling between VT windings is tough, the VT voltage transfer characteristic is nearly flat and relatively weakly dependent on load,
- secondly, for the frequency range where magnetizing and leakage inductances are comparable (Band 2 according to Fig. 12) the VT voltage transfer characteristic is hardly dependent of VT load character and the influence of internal distribution of parasitic capacitances of winding is manifested by extra local parasitic resonance occurrence.

Additional effects of parasitic capacitance distribution, which are not sufficiently represented by evaluated simplified circuit model, justify narrower pass band of VT obtained by experimental investigation (about 2 kHz) with comparison to simulation results (about 20 kHz).

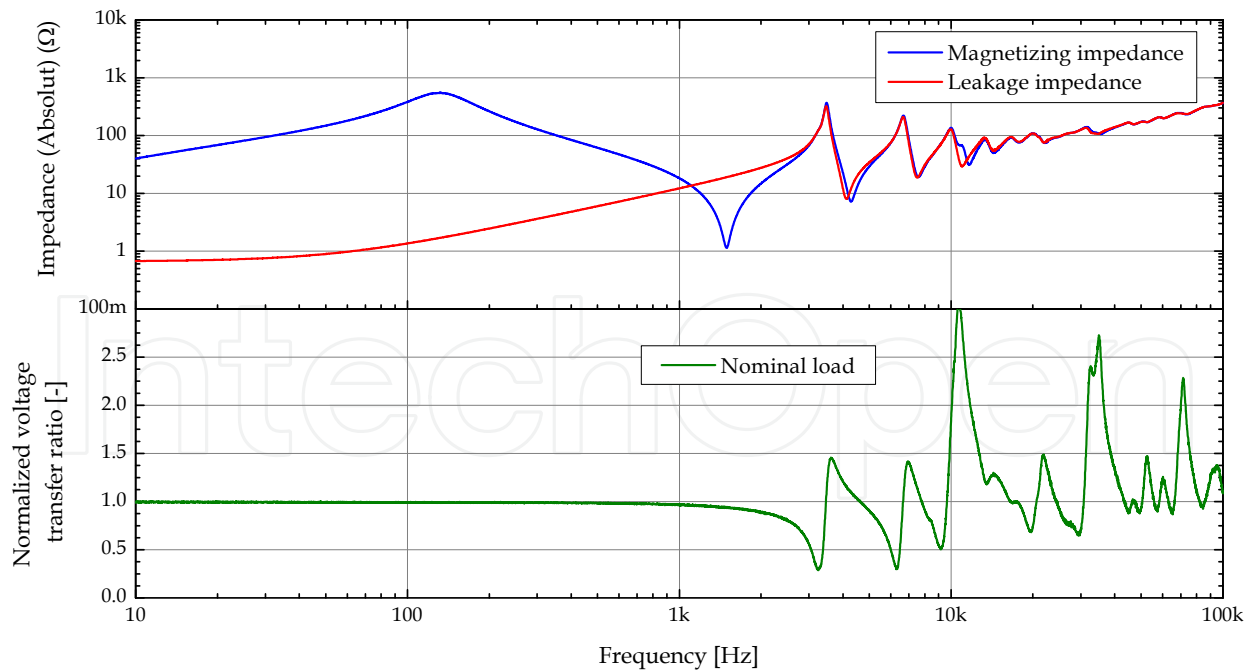


Fig. 18. Correlation between measured VT voltage transfer characteristic and magnetizing and leakage impedance-frequency characteristics

Accurateness of magnitude and phase voltage transfer characteristics of VT is a fundamental aspect for identification and measurement of power quality related phenomena in power system. For the investigated VT the voltage transfer ratio and voltage phase shift characteristics have been measured to reveal measurement accuracy problems of power quality assessment in MV systems. Magnitudes versus phase transfer characteristic of VT measured for different frequency ranges typically used in power quality measurement systems (up to 40th harmonic and up to 9 kHz) are presented in Fig. 19 and Fig. 20. Experimental investigations prove that magnitude and phase errors increase noticeably with frequency. In frequency range up to 2 kHz, the highest magnitude error of about 11 % and phase shift error almost 8°, have been obtained for frequency 2 kHz. These results confirm that voltage harmonics measurement in MV grids by using VT can be not accurate enough in applications with noticeable harmonic content above approximately 1 kHz.

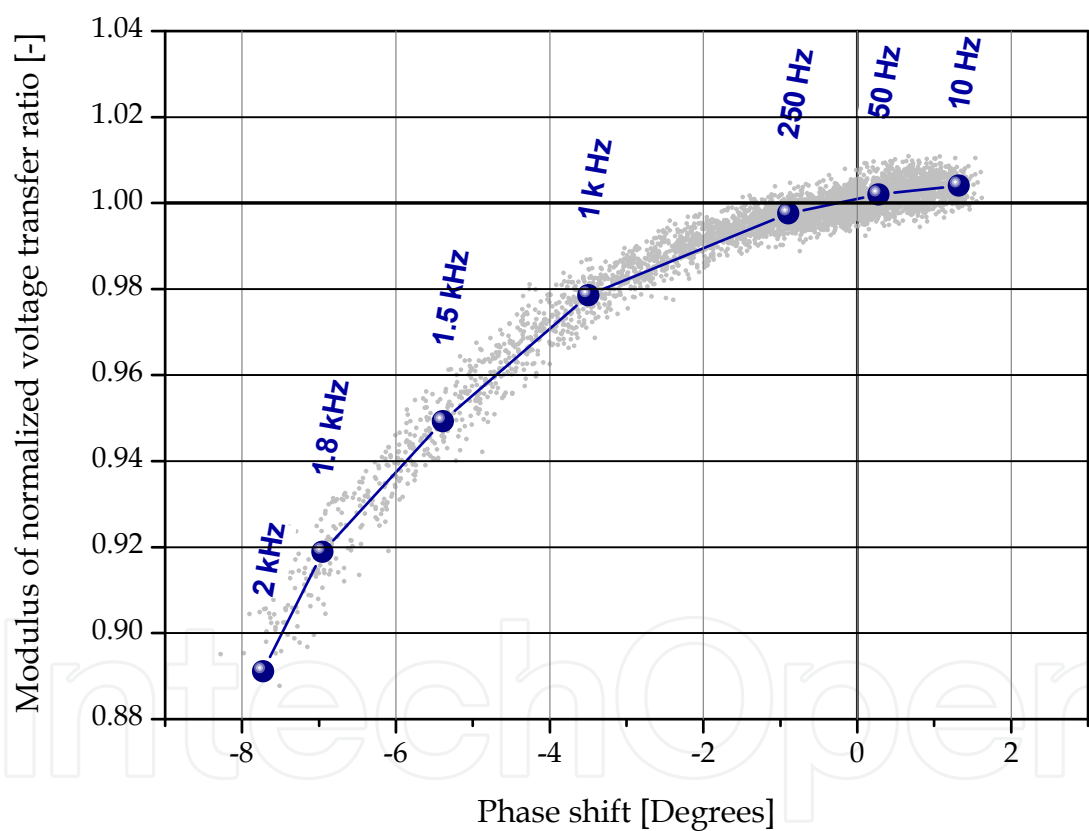


Fig. 19. Normalized VT voltage ratio vs. phase shift angle for frequency band up to 2 kHz

Magnitudes and phase inaccuracy of VT obtained in frequency range from 2 kHz up to 9 kHz (Fig. 20) are evidently greater and its frequency dependence is more complex, therefore more difficult to model using simplified circuit models. Magnitude errors in this frequency range reach almost 180% and phase shift error almost 80°, which cannot be accepted in power quality measurement applications.

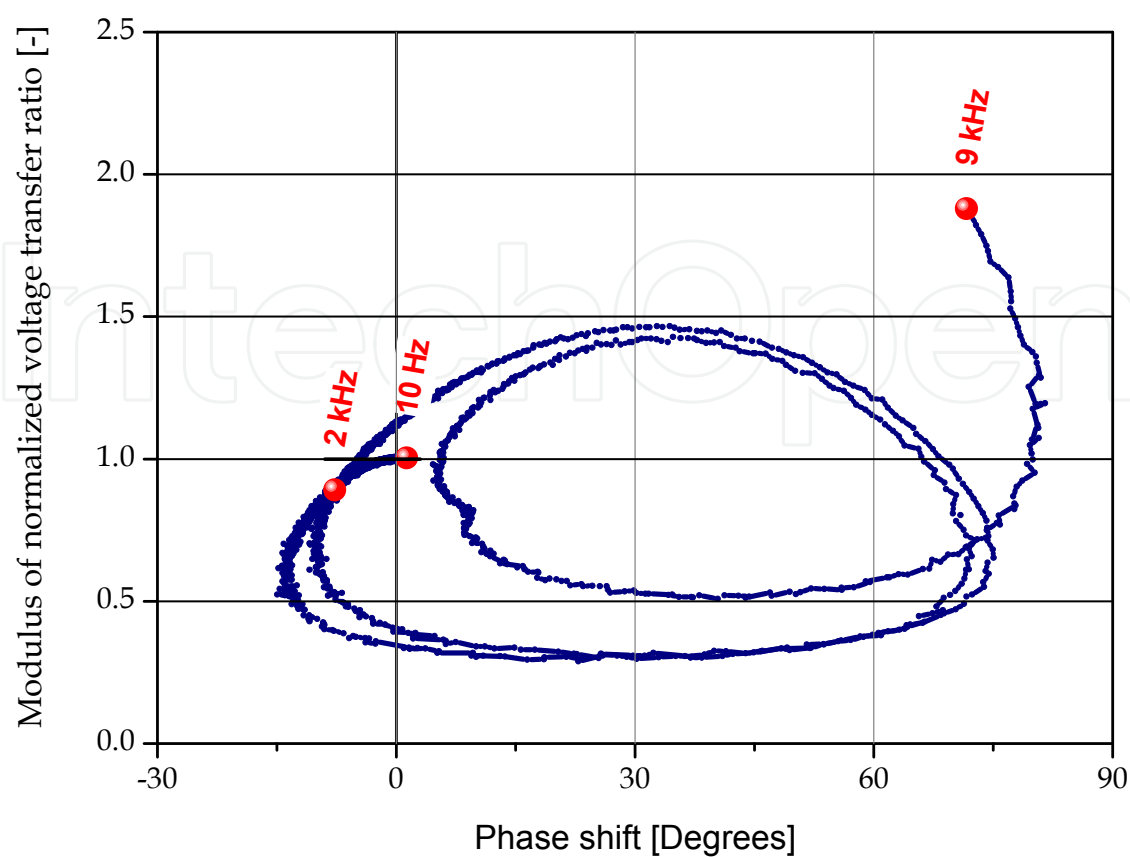


Fig. 20. Normalized VT voltage ratio vs. phase shift angle for frequency band up to 9 kHz

6. Conclusions

Modelling of VT voltage transfer characteristic in wide frequency range is rather challenging. Main problems with accurate modelling using circuit models are related to windings’ parasitic capacitances and especially identification of its unequal distribution along windings. To model the influence of parasitic capacitive couplings existing in a typical VT several simplifications should be considered. The method of VT parasitic capacitances analysis based on the lumped representation is often used and particularly rational, nevertheless limits the frequency range within which acceptable accuracy can be obtained. Its parameters can be determined based only on wideband measurement of leakage and magnetizing impedances, unfortunately it can be successfully used only in the limited frequency range. For typical VT used in MV grids the flatten fragment of transfer characteristic can be obtained usually only up to few kHz. Above this frequency VT usually exhibit a number of resonances which change evidently its transfer characteristic and cannot be reflected adequately by simplified circuit models. Wideband performance of VT in a particular application is also noticeably related to its load level and character (inductive or capacitive). For typical VT it is possible to improve slightly its wideband performance by lowering its load level or by changing its character into inductive, but it usually requires laborious experimental verification. Despite of recognized restrictions and limited accuracy of the developed circuit model it can be successfully used for approximate assessment of VT pass band.

The use of VT in power quality monitoring MV grids influence essentially finally obtained measurement accuracy. In power quality measurement applications where dominating harmonics emission is expected only in frequency range below 2 kHz VTs can provide sufficient accuracy in many applications, nevertheless its voltage transfer characteristic should be carefully verified with taking into account particular operating conditions. Nowadays, much wider than up to 2 kHz harmonics emission spectrum can be injected into the power system, especially by contemporary high power electronic applications. In this frequency range from 2 kHz up to 9 kHz, which is already well specified by harmonic emission limitation standards, typically used VT are not reliable enough. Measurement errors in frequency range up to 9 kHz are usually not acceptable, because of resonance effects which commonly appear and are difficult to predict.

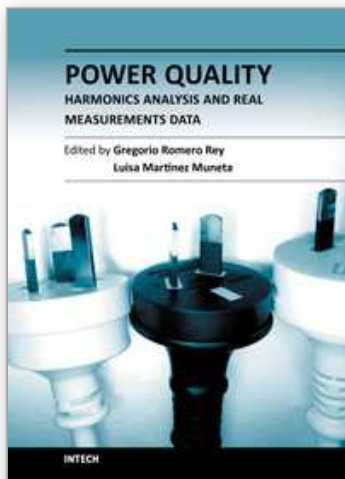
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Nowadays, the increasing use of power electronics equipment origins important distortions. The perfect AC power systems are a pure sinusoidal wave, both voltage and current, but the ever-increasing existence of non-linear loads modify the characteristics of voltage and current from the ideal sinusoidal wave. This deviation from the ideal wave is reflected by the harmonics and, although its effects vary depending on the type of load, it affects the efficiency of an electrical system and can cause considerable damage to the systems and infrastructures. Ensuring optimal power quality after a good design and devices means productivity, efficiency, competitiveness and profitability. Nevertheless, nobody can assure the optimal power quality when there is a good design if the correct testing and working process from the obtained data is not properly assured at every instant; this entails processing the real data correctly. In this book the reader will be introduced to the harmonics analysis from the real measurement data and to the study of different industrial environments and electronic devices.

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